# Caractérisation des conditions de site de 33 stations du Réseau Accélérométrique Permanent français (RAP)
# Site condition characterization of 33 stations form the French permanent Accelerometric network (RAP)

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*RÉSUMÉ. L'utilisation optimale des bases de données accélérométriques demande à ce que les « métadonnées » associées aux stations accélérométriques et informant sur les conditions de site (Vs30, classe de sol, profil de vitesse…) soient renseignées de manière fiable. Bien souvent, compte tenu du coût des caractérisations de type géotechnique, du nombre de sites à caractériser et de leur difficulté d'accès, les informations de site reposent sur des informations indirectes, comme par exemple l'examen de cartes géologiques. Au cours des 2 dernières années, nous avons mené des actions de caractérisation sur 33 stations RAP (Pyrénées, Auvergne, Alpes) en mettant en œuvre des méthodes non-invasives basées sur l'analyse des ondes de surface. Dans la plupart des cas, nous avons mis en œuvre conjointement des approches « passives » et « actives » afin de pouvoir reconstituer une courbe de dispersion sur la plus large bande de fréquence possible. Les résultats montrent que dans de nombreux cas, les précédentes estimations de Vs30 et de classe de sols étaient surestimées. C'est souvent la présence d'une couche de quelques mètres de roche altérée ou de dépôts quaternaires (colluvions), non représentés sur les cartes géologiques, qui implique ces évolutions. Ces couches provoquent également souvent la présence d'un effet de site (amplification) « haute fréquence ».*

*ABSTRACT. The optimal use of accelerometric database needs reliable "metadata" (providing information about site conditions: Vs30, soil class, velocity profile...). Often, taking into account the cost of geotechnical characterization, the number of sites to characterize and the station access difficulty, metadata are based on indirect information, such as the use of geological maps. Over the past two years, we have conducted the characterization of 33 RAP stations (Pyrenees, Auvergne, Alpes) by implementing non-invasive methods based on the analysis of surface waves. In most cases, we have jointly implemented "passive" and "active" approaches in order to build a dispersion curve on the widest possible frequency band. The results show that in many cases, previous estimates Vs30 and soil class were overestimated. It is often the presence of a layer of a few meters, made with weathered rock or quaternary deposits (colluviums), not shown in the geological mapping, which involves these evolutions within the soil class attribution. These layers also often involve the presence of a "high frequency" site of effect (amplification).*

*MOTS-CLÉS : $V_S30$, classe de sol, méthodes non-invasives, caractérisation de site, ondes de surface, RAP.*

*KEYWORDS: $V_S30$, soil classes, non-invasive methods, site characterization, surface waves, RAP.*

## 1. Introduction

Data provided by accelerometric network are important for seismic hazard assessment. They are especially used to derive Ground Motion Prediction Equations (GMPEs). The correct use of accelerometric signal is closely linked to the station site metadata that should provide reliable information about site class, Vs30 value, velocity profiles, and all relevant information that can help to quantify the site effect associated to stations.

In France, the permanent accelerometric network ("RAP" for "Réseau Accélérométrique Permanent") consists in around 150 stations. We present here a recent effort that led to the characterization of 33 stations, in the South part of France. These stations are briefly presented in paragraph 2. This characterization was performed using surface-wave based methods that allow deriving velocity profiles from dispersion curves of Rayleigh and Love waves. We implemented both active acquisitions (Multichannel Analysis of Surface Waves) and passive acquisitions (Ambient Vibration Array) using multiple circle arrays. The standard acquisition setup is described in paragraph 3 whereas paragraph 4 presents in details the applied processing, taking one station as an example. The computation of dispersion curves, then the inversion in terms of shear wave velocity profiles (taking into account the non- uniqueness issue of such inversion) allowed also defining Vs30 values and soil class with corresponding uncertainties. Paragraph 5 summarized the results and comments the differences with respect to previous studies. It is worth noting that even for so called "rock sites" (Vs30 > 800 m/s), we almost ever identified a very shallow weathered zone that may be responsible for a high frequency site effect. This one has to be taken into account for a better phenomenological understanding of "high frequency content" of rock station accelerograms (see paragraph 6). From a methodological point of view (paragraph 7), this survey leads to the following recommendations. 1) Perform both active and passive measurements in order to derive dispersion curves on a wide frequency range. 2) Perform active acquisitions for both vertical (Rayleigh wave) and horizontal (Love wave) polarities. This helps to better determine dispersion curve modes and thus decreases the risk of errors in velocity profile derivation.

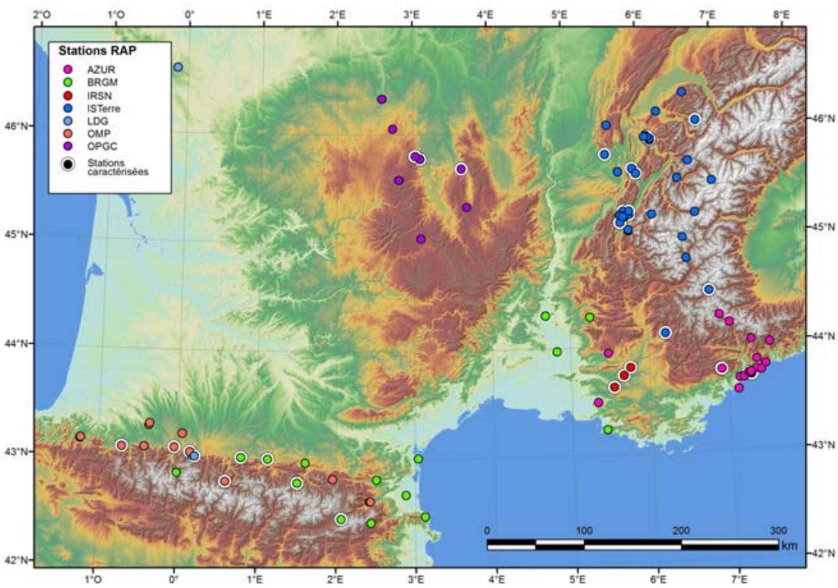


**Figure 1:** *Map of the south half of France with location of RAP network stations and stations that benefited of the characterization presented in this paper.*

## 2. Choice of RAP stations

The choice of stations was a compromise between different parameters. We wanted to characterize stations that were used as “reference stations” within the previous work of Drouet *et al.* 2010. We also wanted to characterize stations that produced a high amount of accelerograms. 9 stations were chosen in the Pyrenees area, 3 in Auvergne, 6 in the South part of Alps (Provence and “Cote d'Azur”), 15 in Alps. Figure 1 shows the location of these stations within the whole RAP network.The first surveys were organized in 2012, the last ones finished in January 2015. The processing of 22 surveys is presented here.

## 3. Overall survey layout and acquisition

The basic acquisition layout consists in the acquisition of both passive (AVA: Ambient Vibration Array) and active (MASW: Multi Analysis Surface waves) surface-wave acquisition. The standard layout was this one:

For MASW acquisition, we used a 24 channel device with 4,5 Hz geophones placed along a line of 46 m, with an geophone inter-trace of 2 m. We stroke the ground with a 4 kg hammer on both side of the line (Figure 2). We performed the acquisition with both vertical polarization (for Rayleigh wave analysis) and horizontal polarization (for Love wave analysis). For AVA acquisition, we usually used circle geometries with one sensor in the centre and 7 equally-spaced sensors on the circumference of a given radius circle. Acquisitions were made with 15 broad-band seismometers. This number of sensors allowed recording two circular arrays at once (Figure 3). A radius ratio of 3 was chosen to increase two consecutive array radii, starting from a 5 m radius circle up to a 405 m radius circle. For consecutive acquisitions, only the inner/smaller circle was moved to the next larger diameter. Hence, the different sets of acquisitions are:

- Array #1 (called “R1-R2”): center + 5 m and 15 m radius circles,
- Array #2 (called “R2-R3”): center + 15 m and 45 m radius circles,
- Array #3 (called “R3-R4”): center + 45 m and 135 m radius circles,
- Array #4 (called “R4-R5”): center + 105 m and 405 m radius circles.

Of course, this standard layout was adapted to take into account logistical constraints. For the Pyrenees and Auvergne stations surveys, performed in 2012, we just had 10 sensors and we use single circle geometries. For (a priori) rock sites, we usually skip Array #1 (due to lack of energy at high frequency and high velocity) and we instead performed two MASW lines (the standard one with its 46 m line and 2 m spaced geophones and a second one with a 92 m line and 4 m spaced geophones). For sites with very difficult access, we also sometimes skip Array #4.

**Figure 2:** *Left: MASW line near the CALF station. Right: MASW acquisition (4 kg hammer source) near the OGCH station.*


**Figure 3:** *Left: location of the 15 broadband seismometers on a double circle geometry (here, with radii of 15 and 45 m) at the OGAP station. Right: inner circle (radius = 5 m) of an AVA acquisition near the OGAP station.*

## 4. Example of a compete processing: the OGIM station

*Overall geological context:*

The OGIM site is located in the north-east of Grenoble in the clayey cone of Saint-Ismier (end Würmien – Holocene). It is surrounded by torrential cones interstratified in recent alluvial deposits (Holocene to current). Marlous deposits (middle and higher Jurassic) outcrop to the south-west of the site.

*Processing results:*

All processing was performed with the Geopsy software package (Wathelet 2008).

In order to check the overall quality of data, we computed Fourier amplitude, and then the ambient vibration H/V curves (Figure 4). The H/V analysis can provide the fundamental frequency of the site (that could be include later within the inversion) and give information about the possible lateral heterogeneity, especially for large array.

On AVA arrays, we systematically applied FK processing, high resolution FK (HRFK) processing and MSPAC processing. The results are shown Figure 5. Then the dispersion curves (DCs) associated to each geometry / processing type were picked (when possible), with respect to the wave-number validity range. In our example, MSPAC did not produce clear information for Array R4R5.

For MASW (Figure 6), both vertical (Rayleigh) and horizontal (Love) polarization were processed, for each shot position, then the “beampower” was picked, also respecting validity range criteria.

Then, the different DCs curves are gathered (Figure 7). When FK (or HRFK) and MSPAC produced different DCs, we checked the back-azimuth of dominant vibrations. Indeed, MSPAC approach assumes that the vibration sources are homogeneously distributed in azimuth. When this assumption is not respected, we avoided to use MSPAC results.

Then the inversion was performed. In the OGIM case, inversion results were obtained after 300300 models. Figure 8 displays the best shear- wave velocity profile (red line) as well as the ensemble of shear-wave velocity profiles that explain the data within their uncertainty bound following the “acceptable solution” concept. Theoretical dispersion curves obtained from this ensemble of ground models are also shown together with the observed phase velocities.

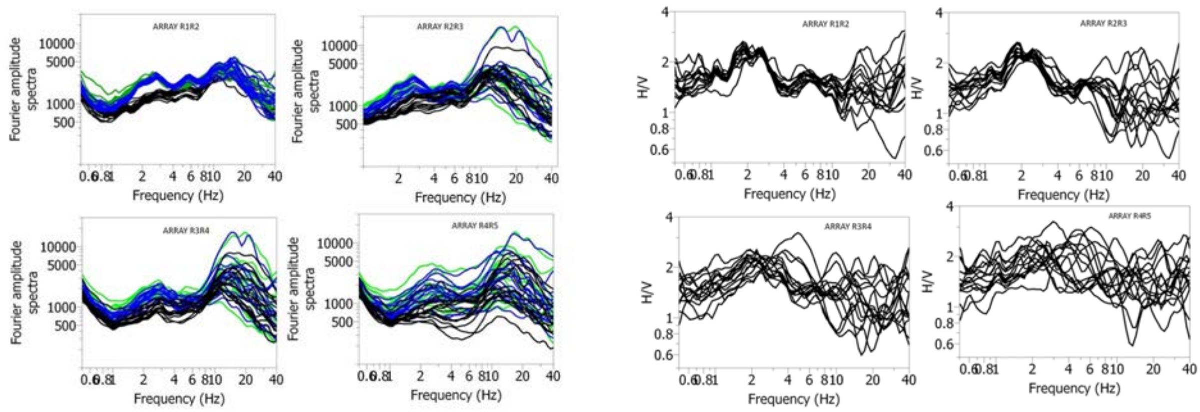


**Figure 4:** *Left: Fourier spectra of all sensors and arrays for the OGIM survey. Right: ambiant vibration H/V ratio for all sensors and for all arrays.*

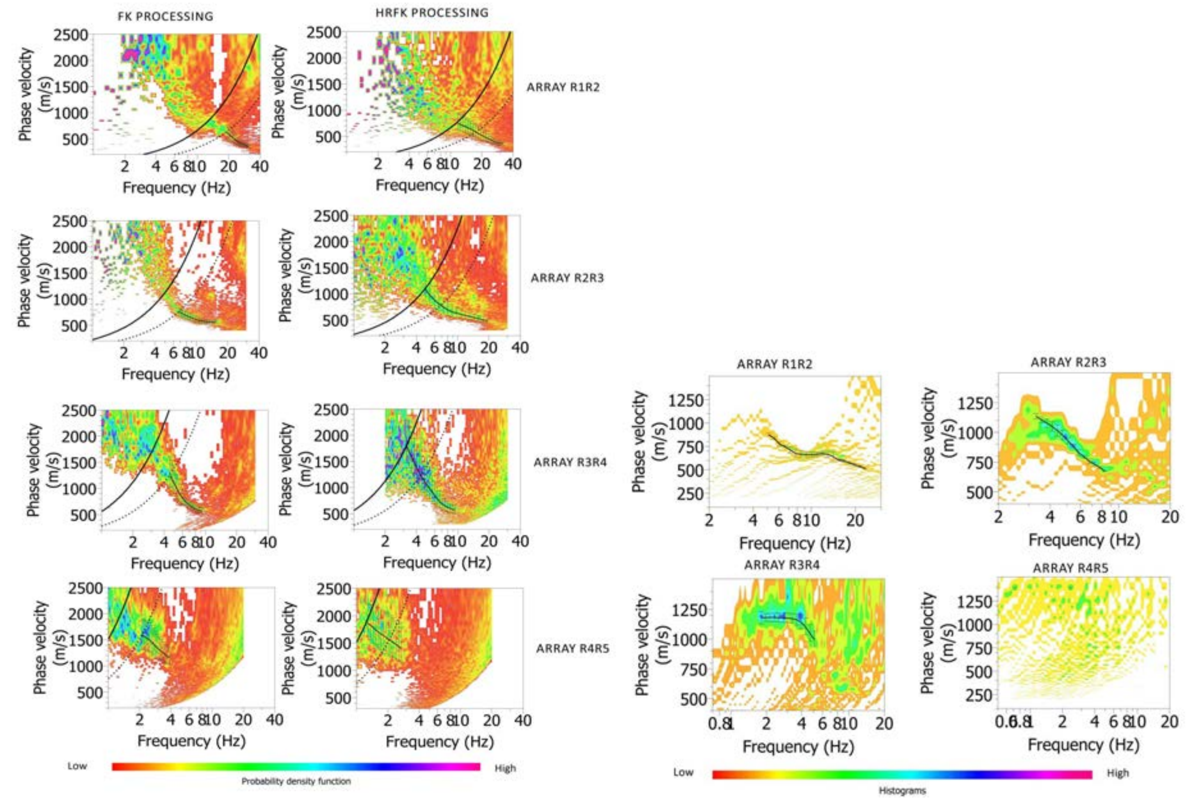


**Figure 5:** *Left: FK and HRFK processing and corresponding picked DCs for all arrays of the OGIM survey. Right: MSPAC processing and corresponding picked DCs for all arrays of the OGIM survey.*

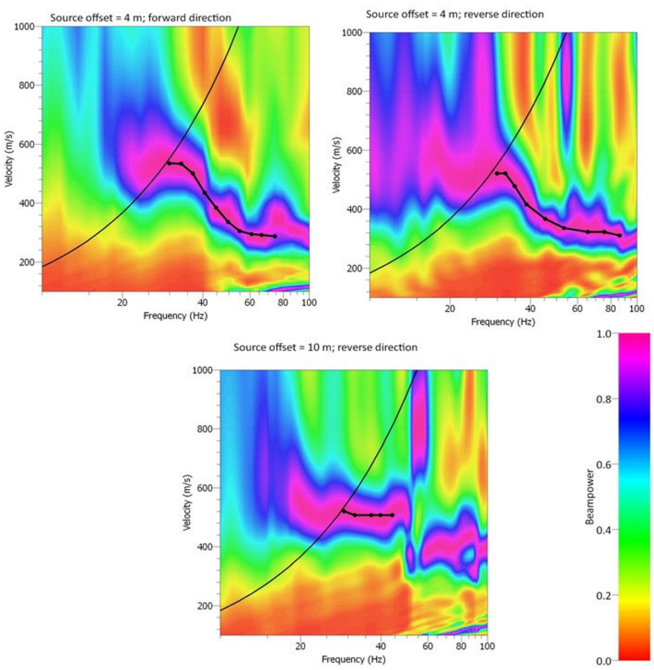


**Figure 6:** *MASW "beampower" processing and corresponding picked DCs for all horizontal (Love) polarization and shot locations.*

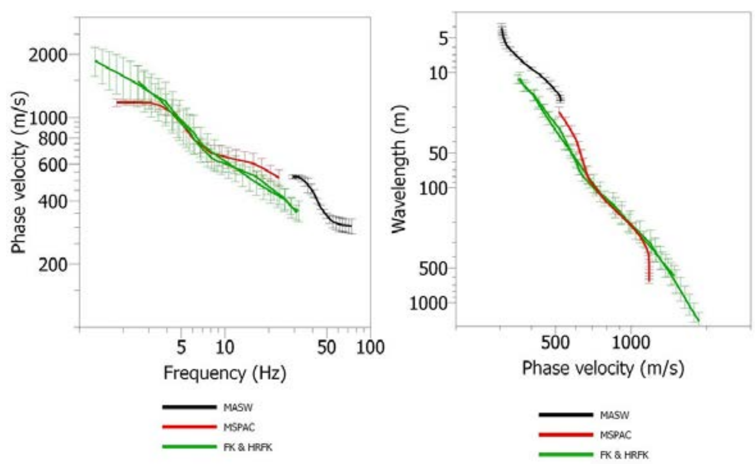


**Figure 7:** *Merge of all dispersion curves in both frequency-velocity plot (left) and wavelength-velocity plot (right).*

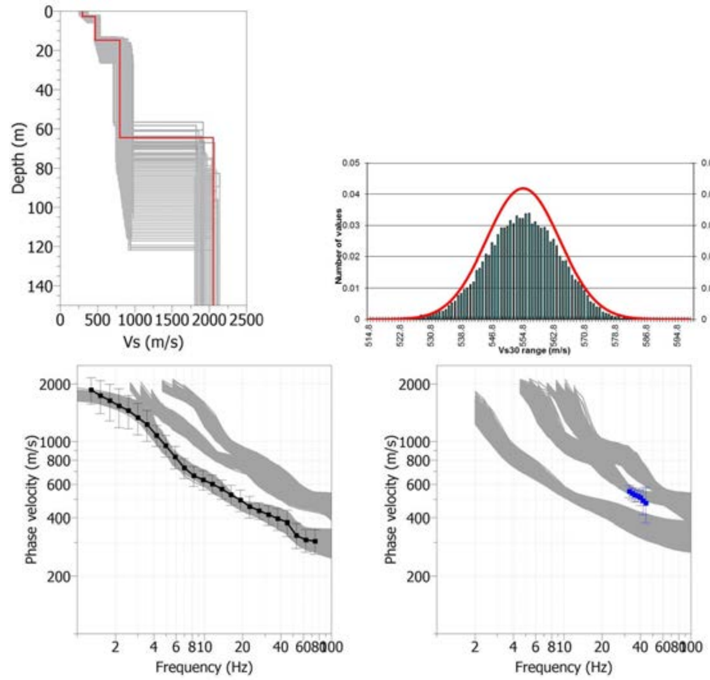


**Figure 8:** *Inversion results. Left: ensemble of statistically acceptable Vs profiles explaining the observed dispersion data within their uncertainty bounds. The red line shows the best misfit profile. Bottom: theoretical dispersion curves computed from the ensemble of inverted shear-wave velocity profile for Rayleigh phase (left) and Love phase (right).The dots indicate measured phase velocities +/- standard deviation.*

## 5. Results – Soil class reattributions

The results for each station led to the furniture of a set of "acceptable" velocity profiles and the best estimated velocity profile. For few stations (especially in the Pyrenees where the acquisition did not benefit of the same redundancy of sensors and variety of array dimensions than in Alps), different hypothesis of mode attributions were addressed, leading to few sets of results. These results could then be derived in terms of Vs30 and EC8 soil classes. The Table 1 shows these results for the 22 stations for which the processing is now over. For two stations (both from Pyrenees, with the above mentioned limitations) the recorded data was not good enough to derive velocity profile at a significant depth.

In comparison with previous works on RAP station soil class estimation (this comparison could be done on 17 stations since they were studied by both works): 3 previously assumed "A class" stations are now downgraded to B class; 1 previously assumed "A class" station is now downgraded to C class; 1 previously assumed "B class" station is now downgraded to C class. No "upgraded" station was found. In terms of Vs30 values, 13 stations have now lower values than the previous estimation, 2 stations have now higher Vs30 value, 2 remain unchanged (within a +/- 10% range).

This overall observation shows that soil quality of network stations are usually overestimated when classification are not based on in situ measurements (this was already observed on other networks, like in Italy, see e.g. Pileggi *et al.* 2011).

**Table 1.** *Summary of the main results in terms of Vs30 and EC8 soil class. We also indicate the maximum depth of the obtained velocity profile.*

| RAP station name | Vs30 [m/s] | Maximum depth of computed profiles [m] | EC8 soil class |
|---|---|---|---|
| EPF | ? | 5 | ? |
| PYAS | 1000 | 130 | A |
| PYAT | 1100 | 250 | A |
| PYBB | 750 | 160 | B |
| PYLI | 1000 | 130 | A |
| PYLL | ? | 3 | ? |
| PYLO | 780 | 60 | A or B |
| PYLU | 380 | 130 | B |
| PYOR | 310 | 60 | C |
| GRN | 810 | 25 | A or B |
| IRVG | 2000 | 55 | A |
| OGAN | 1100 | 280 | A |
| OGAP | 260 | 100 | C |
| OGCH | 1400 | 300 | A |
| OGDH | 220 | 300 | C |
| OGIM | 550 | 150 | B |
| OGLE | 780 | 25 | A or B |
| OGMA | 850 | 220 | A |
| OGME | 390 | 320 | B |
| OGMU | 760 | 25 | B |
| OGPC | 510 | 300 | B |
| SURF | 420 | 60 | B |

## 6. Implication: is there any reference station?

8 sites out of the 22 investigated sites presented here (PYAS, PYLI, PYLL, PYLO, OGAN OGCH, OGLE, and OGMU) were previously considered by Drouet et al. (2010) as reference stations within a generalized inversion work. Within this work, these stations were assumed to have a Vs30 value of 2000 m/s. All Vs30 values determined within the framework of the present work are much lower.

Beyond the discussion about the Vs30 values, on important issue is the notion of “reference station”. If we focused on PYAS and PYLI, even if these two sites belong clearly to the EC8 “A” soil class, they both show a thin layer of low-velocity material with a thickness of few meters (due to a weather zone or thin quaternary colluvium deposits). This leads to a very high frequency site effect. The Figure 9 illustrates this feature showing the 1D transfer functions computed with “best estimated” and the one thousand profile sets for both PYAS and PYLI sites. The “A class” information is definitely not sufficient to characterize accelerometric site.

## 7. What about the impact on k0 estimation?

The kappa parameter is now widely used and discussed. Its impact on seismic hazard assessment can be huge. Kappa is usually measured on earthquake records at high frequency (typically above 10 Hz) and aims to characterize the attenuation at high frequency. The common interpretation considers usually that when kappa is low, this mean that high frequencies are weakly damped at a scale of few hundred meters to few kilometers beneath the studied site. If kappa is high, this is usually explained as a high damping of high frequencies at the same scale.

From a statistical point of view, “rock station” usually shows low kappa values and this means, at the first order, that the high frequency content of earthquake records is high. But is this feature only due to a lack of attenuation at a hecto- to kilometric scale or this could also be due to high frequency site effect? The Figure 10 shows the site response of PYAS and PYLI obtained by GIM performed by Drouet *et al.* (2010) and corresponding kappa estimation. On PYAS, one can guess the high frequency site effect (bump between 10 and 20 Hz). This clearly affects the kappa estimation. On PYLI, one does not see this effect but here, the possible local site effect (> 25 Hz) is at an even higher frequency.

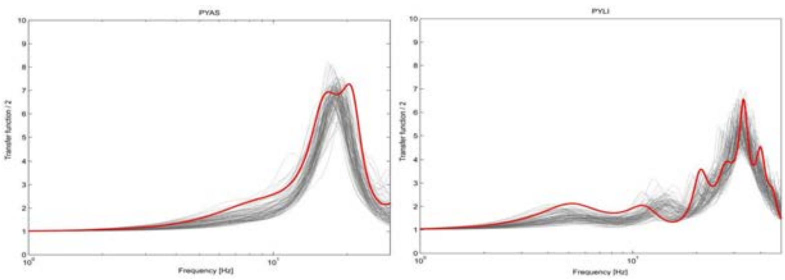

**Figure 9:** *1D transfer functions computed with “best estimated” Vs30 profile (red) and the one thousand profile sets deriving from the “acceptable misfit” approach (gray) for both PYAS and PYLI sites.*

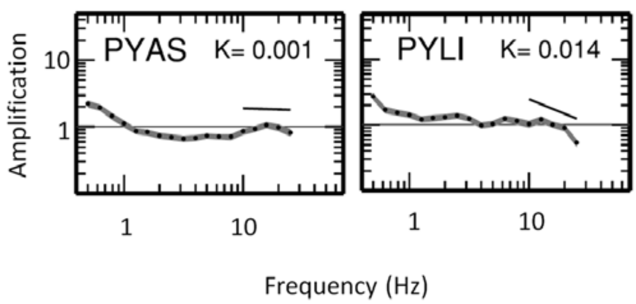


**Figure 10:** *Site transfer functions ± one standard deviation for the horizontal component (black line and dark grey shaded area) for PYAS and PYLI from generalized inversion of Drouet et al. (2010). Solid lines indicate the regression of the high frequency part of the transfer functions, which leads to the κ-values indicated on top of each frame.*

## 8. Methodological feedback and conclusions

Even if logistical context is sometimes difficult, using surface-wave based methods are suitable for accelerometric station characterization, even on rock sites (where the applicability of these methods was sometimes disputed).

It was usually possible to achieve a complete survey for one station in one working day, with 5 to 6 motivated operators when the weather was OK… Conversely, the processing is time consuming (one working week for one geophysicist) and the inversion procedure have to be supervise by an expert in surface wave methods.

We recommend the use of a rather high number of sensors for AVA (15 sensors in our study) with the proposed double-circle geometry. The difference within the result quality between the Pyrenees stations (where we was not able to use double-circle geometry) and Alps is high. We also strongly recommend the joint use of active (MASW) and passive (AVA) methods in order to get “broadband” dispersion curves. The use of Love wave (for MASW in our case) is also very valuable in the inversion process in order to reduce the risk of misattribution of surface wave modes.

## 9. Acknowledgments

This work was conducted within the framework of the CASHIMA (funded by CEA, ILL and ITER Organization) and SIGMA (funded by EdF, CEA, Areva and Enel) research programs.

We would like to thank all the contributors of this work (especially for help on the field) who are not in the author list due to lack of place: Alice RENAULT (Soldata), Anne LOEVENBRUCK (CEA/LDG), Anthony BONJOUR (BRGM), Aurore LAURENDEAU (CEA/LDG), Catherine PEQUEGNAT (ISTerre), Cécile CRETIN (ISTerre), Cédric GUYONNET BENAIZE (CEA/CAD), Claire LABONNE (CEA/LDG), Clément DESBORDES (CEA/CAD), Corine LACAVE (Résonance), David WOLYNIEC (ISTerre), Déborah SICILIA (EdF), Didier BRUNEL (GeoAzur), Diego MERCERAT (CEREMA), Emeline MAUFROY (ISTerre), Emmanuel CHALJUB (ISTerre), Etienne BERTRAND (CEREMA), Florence RENALIER (Soldata), Franck GRIMAUD (OMP), Franck TILLOLOY (BRGM), Isabelle DOUSTE-BACQUE (ISTERRE), Isabelle DOUSTE-BACQUE (ISTerre), Jean LETORT (ISTerre), Jean-Pierre DESLANDES (ISTerre), Julie REGNIER (CEREMA), Laetitia FOUNDOTOS (CEA/CAD), Marc WATHELET (ISTerre), Mathieu CAUSSE (ISTerre), Michel PERNOUD (CEREMA), Mickaël LANGLAIS (ISTerre), Paul CALOU (CEA/LDG), Philippe GUEGUEN (ISTerre), Pierre-Yves BARD (ISTerre), Robin BARBIER (BRGM), Roser HOSTE-COLOMBER (CEA/LDG), Sadrac SAINT FLEUR (GeoAzur), Stéphane NETCHSCHEIN (IRSN), Sylvette THOMASSIN (Résonance), Vincent BOUTIN (CEA/LDG), Vincent PERRON (CEA/CAD).

## 10. Reference

Drouet S., Cotton F. and Gueguen Ph., *Vs30, κ, regional attenuation and Mw from accelerograms: application to magnitude 3–5 French earthquakes*, 2010, Geophysical journal international, doi: 10.1111/j.1365-246X.2010.04626.x.

Pileggi D., Rossi D., Lunedei E. and Albarello D., *Seismic characterization of rigid sites in the ITACA database by ambient vibration monitoring and geological surveys*, 2011, Bull Earthquake Eng (2011) 9:1839–1854.

Wathelet, M., 2008, *An improved neighborhood algorithm: parameter conditions and dynamic scaling*, 2008, Geophysical Research Letters, 35.